APPROACHES TO DEALING WITH METEOROID AND ORBITAL DEBRIS PROTECTION ON THE SPACE STATION

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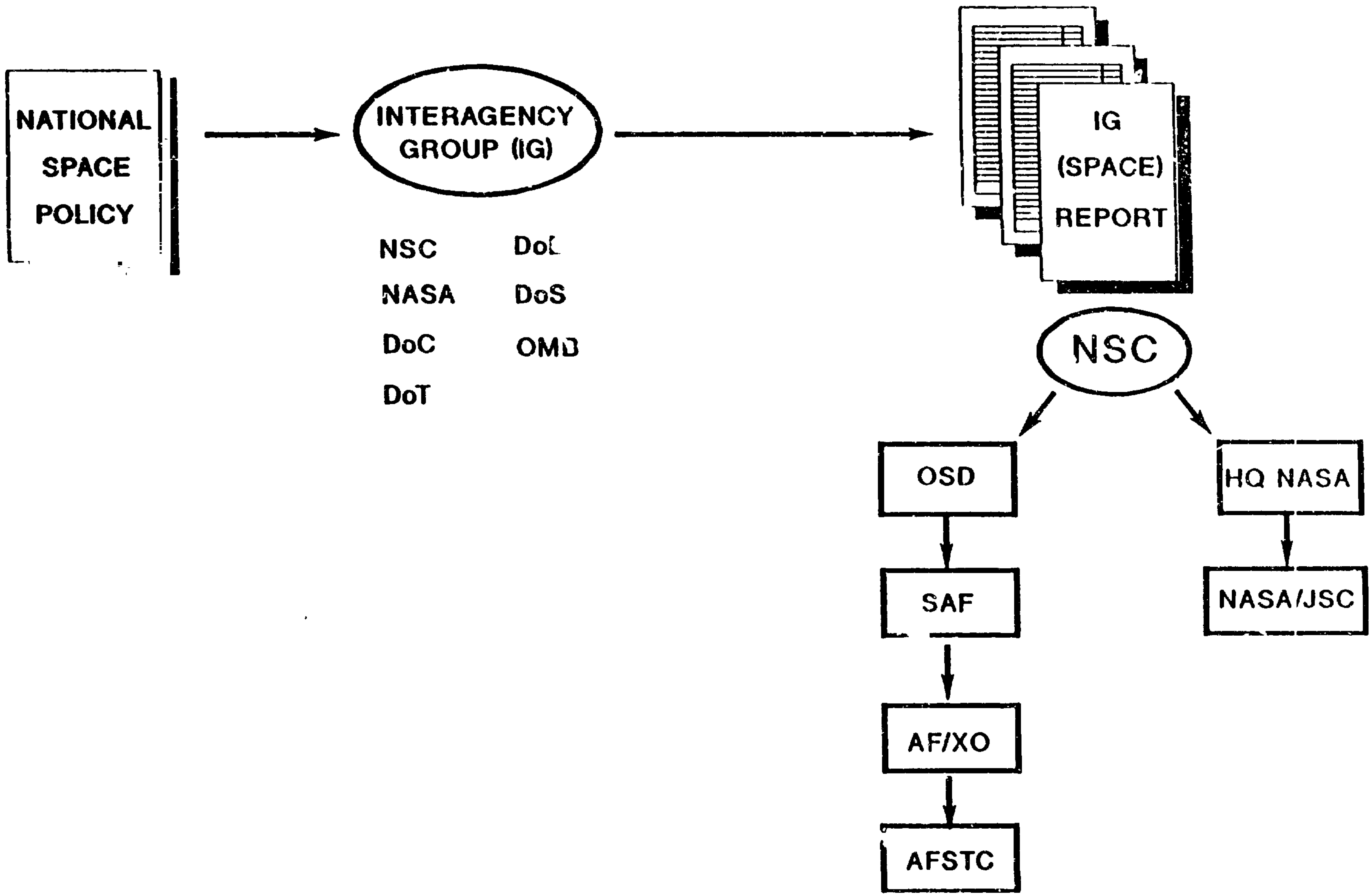
The National Space Policy of February, 1988, included the following: "All sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness." The policy also tasked the National Security Council, which established an Interagency Group, which in turn produced an Interagency Report. This report tasked both NASA and DoD to establish a joint plan to determine techniques to measure the environment, and techniques to reduce the environment.

BACKGROUND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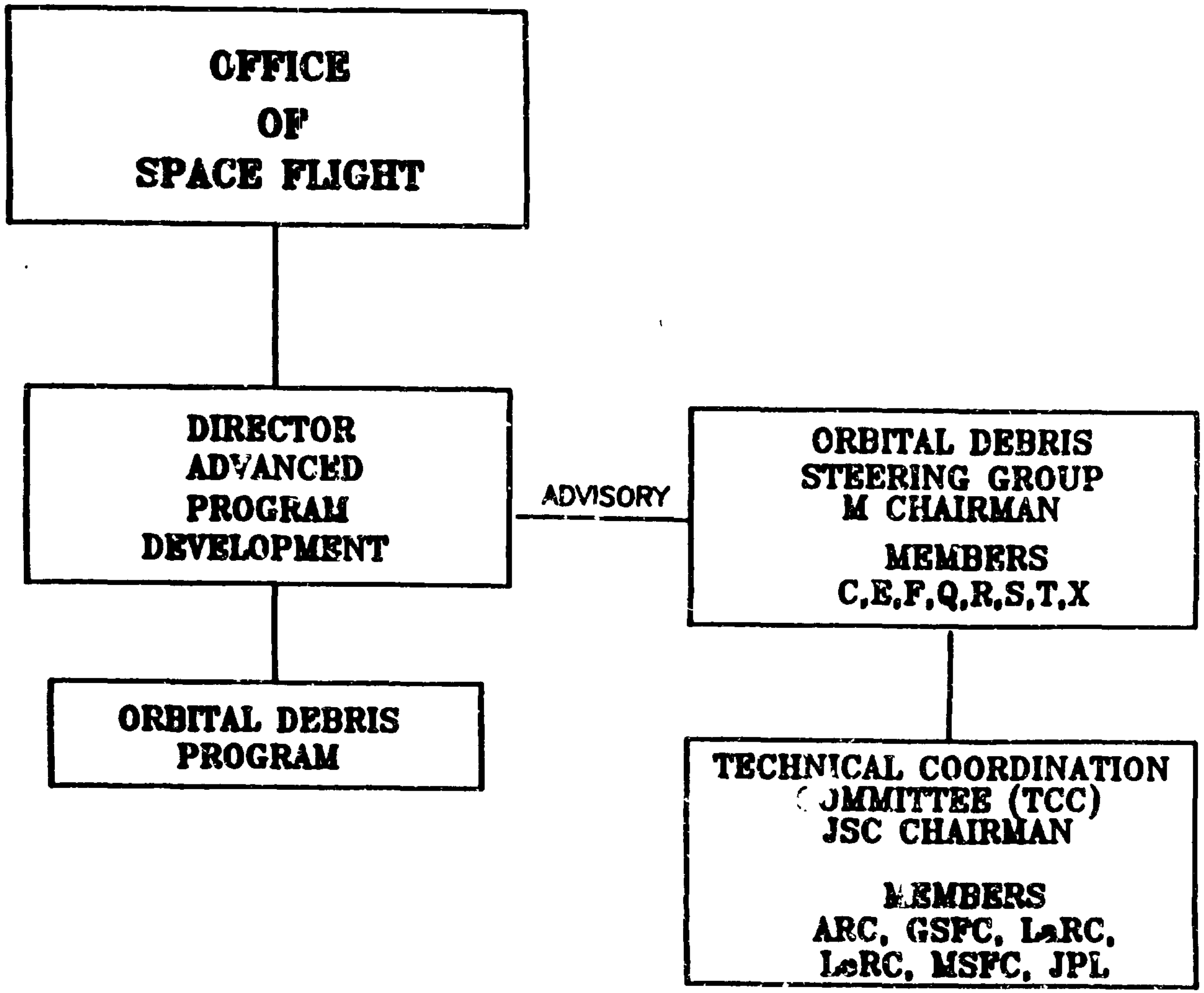
The NASA Administrator directed the Office of Space Flight to Chair an Orbital Debris Steering Group, with representatives from other NASA Offices. A technical Coordination Committee, chaired by the Space Science Branch at the Johnson Space Center was also established.

ORBITAL DEBRIS PROGRAM

MANAGEMENT STRUCTURE



The Johnson Space Center has been studying orbital debris for over 10 years, and has a comprehensive program which includes measurements of both small and large debris, model development, and hypervelocity impact testing. The current largest program is to development a orbital debris radar, with US Space Command, which will statistical monitor the 1 cm, and larger, environment. The largest justification of these measurements is to support Space Station.

NASA/JSC Orbital Debris Program

- Measurements
  - Radar: Maintaining USSPACECOM catalog, breakup measurements, radar development, re-entry radar
  - Optical/IR: GEODSS data acquisition, optical/IR studies, NASA portable telescope
  - Microparticle: PALAPA/WESTAR, LDEF, SOLAR MAX, witness plates, stratospheric dust collection, Space Station Cosmic Dust Facility
- Under development
  - Orbital Debris Radar (Joint USSPACECOM agreement)
  - Radar data processing facility
  - Debris Collision Warning Sensor (visible/IR Shuttle Experiment)
- Data management
  - Modeling: Breakup modeling, population evolution, microparticle environment, current environment assessment, environment forecasts
  - Data Interpretation: Uncorrelated target analysis
- Spacecraft shielding
  - Materials and shielding research, Space Station support, hypervelocity gun development, hypervelocity and low-velocity testing, vulnerability assessment
- Debris management
  - Debris removal, debris prevention
- Facilities
  - Image processing facility, hypervelocity impact research laboratory, electron microscopy laboratory, facility for optical inspection, material archives, telescopic laboratory

Space Station must deal with the entire spectrum of orbital debris sizes. Below 1 cm to 2 cm, shielding is planned; however, the weight of required shielding is sufficiently high that extra shuttle flights could be required to construct the Space Station. For this reason, the approach of adding shielding after the Space Station is constructed is likely. If so, the technique that shielding is added becomes important; since extra EVA also means extra risk, some new techniques of adding shielding may be required.

For sizes between 1 cm and 10 cm, there is currently no proven technique to defend against these particles. During the 30 year life of the Space Station, it is likely that such a size debris particle will collide with the Space Station, if no actions are taken. The collision would most likely be in a non-critical area; however, it would be sufficiently energetic that secondary ejecta would likely damage critical areas. Objects as large a 1 meter are in orbit, and not catalogued.

Collision avoidance is planned for all catalogued objects. A critical question, not yet resolved, is whether US Space Command orbital projections are sufficiently accurate to keep the frequency of maneuvers of the Space Station within acceptable limits.

ORBITAL DEBRIS ENVIRONMENT: ISSUES FOR SPACE STATION FREEDOM

DEBRIS SIZE RANGE	ISSUE	POTENTIAL SOLUTIONS	PROBLEMS TO SOLUTION IMPLIMENTATION
Less than 1 cm (2 cm)	Loss of critical elements due to direct impact; damage to non-critical elements due to direct impact and secondary ejecta.	• Shielding • Maintaince • Re-dundant systems	• Weight limitations - new materials - Add -on shielding • Additional EVA
1 cm to 10 cm (1 meter)	Loss of critical elements damage to non-critical elements due to secondary ejecta from direct impact of non critical areas. Potential loss of station from catastrophic collision.	• Increased Ground tracking capabilities • On-board collision warning sensor - Active shielding - Heavly shielded shelter - Directed energy diversion • Materials which minimize secondary ejecta	• Technology development
Larger than 10 cm (1 meter)	Loss of Station from catas[illegible] collision	• Collision avoidance using ground tracking	• US Space Command Limitations - Accuracy of tracking - Completeness of data • Frequency of maneuvers

Knowledge of the meteoroid environment is primarily the result of the past 25 years of research. The understanding of the environment has not changed significantly since 1970. A very small amount of meteoroid mass is passing through Earth orbital space at about 20 km/sec; even so, meteoroids are a design consideration for the Space Station.

Meteoroid Background - Current NASA Understanding

- Best data from meteors, deep space sensors, lunar rocks, returned spacecraft surfaces, and early sensors requiring penetration
- Meteoroid orbits pass through Earth orbital space (none believed to be in Earth orbit)
- Less than 200 kg at altitudes below 2000 km at any one time (most approximately 0.1 mm in diameter)
- In the past, meteoroids have occasionally affected spacecraft design
  - Apollo, Skylab
  - Size range 0.3 mm to 3 mm most important
- In the future, meteoroids are expected to be more important
  - Larger spacecraft
  - Longer exposure
  - Lighter weight construction
  - Size range 0.1 mm to 1 cm will be important

The meteoroid environment used of to design spacecraft is given in NASA SP 8013, published in 1969, and shown here as a cross-section area flux. Assume the surface area of a critical element to be shielded is 100 sq. meters; its average cross-sectional area would be one forth of that, or 25 sq. meters. The average number of impacts on the area in 10 years would be given by N=FX25X10, where F is the cross-sectional flux given in the figure. If the desired probability of no penetration is 0.9955 during the 10 years, then N is approximately equal to 1-.9955, or N=0.0045. The design flux is then F=1.8E-5. From the figure, the design meteoroid size is then about 0.5 cm. That is, the protective shield must be designed to protect against a meteoroid 0.5 cm in diameter, traveling about 20 km/sec, in order to achieve this desired level of reliability.

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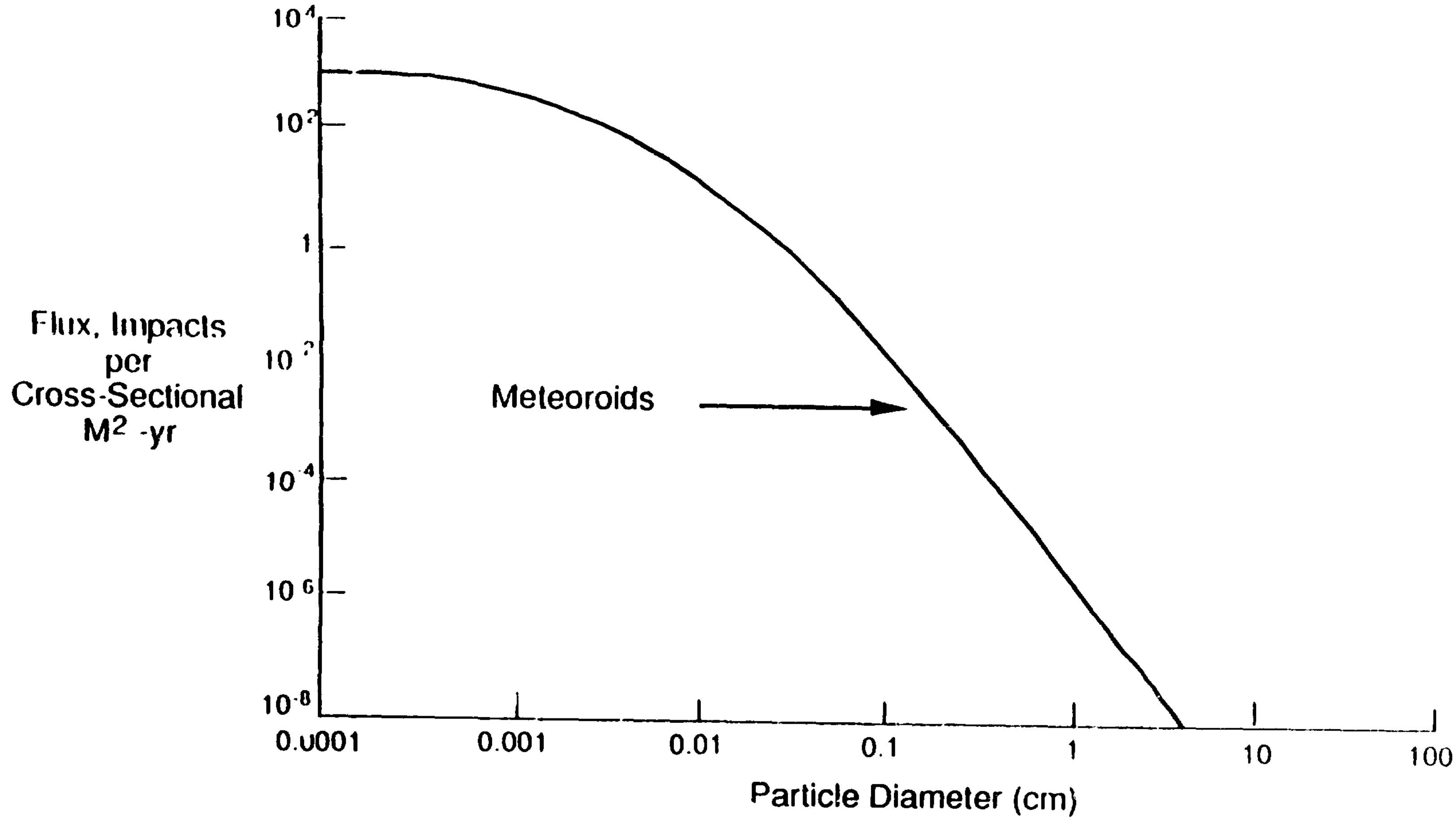
Meteoroid Flux



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Much larger than the meteoroid environment is the amount of mass "permanently" orbiting the Earth in the form of man-made objects. Most of the man-made mass is in relative large, old rocket bodies and payloads, vs. the relative small dust size for meteoroids. However, if only a small fraction of the man-made material were to fragment into the size distribution of meteoroids, the resulting flux would exceed the meteoroid flux. There many ways that the man-made objects can, and have, fragmented.

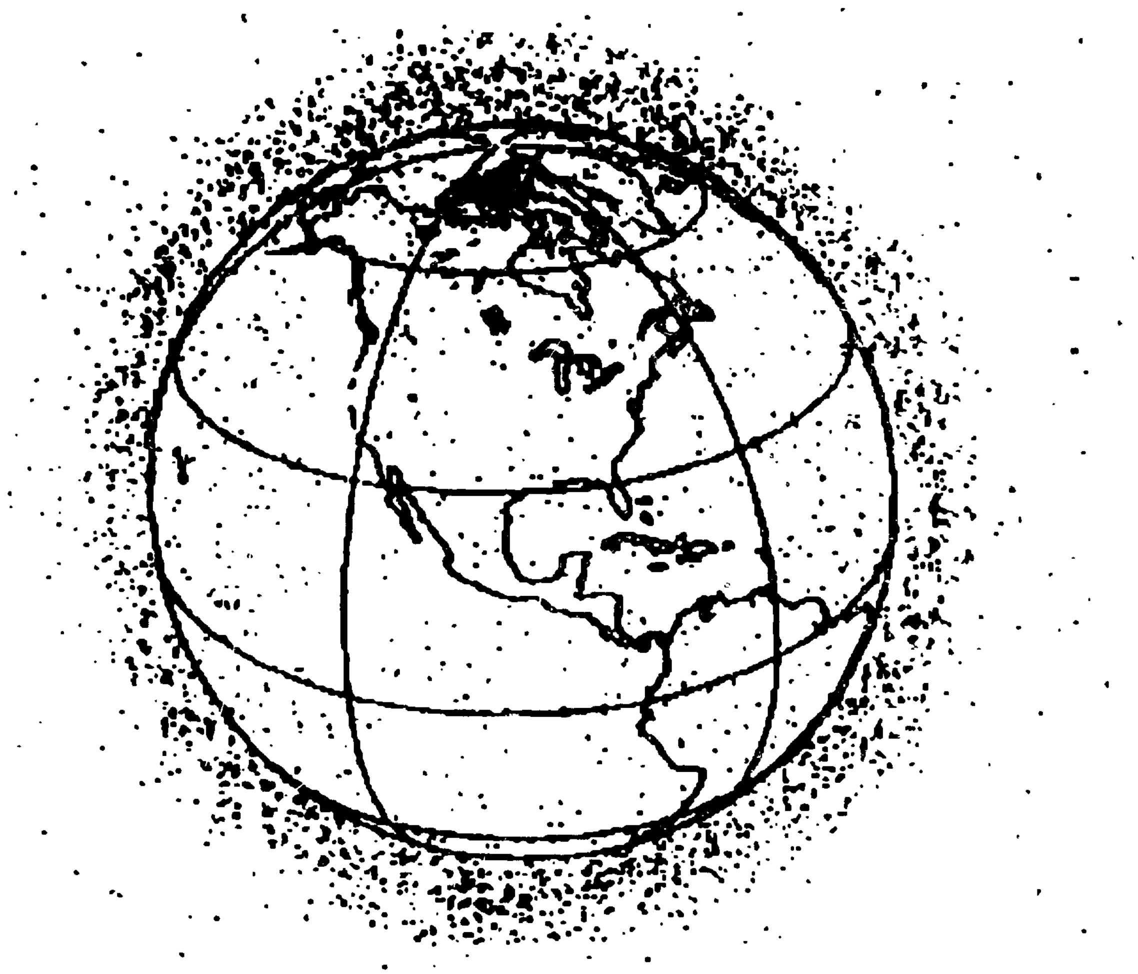
Orbital Debris Population

- Over 20,000 objects catalogued by U.S. Space Command, most "permanently" in Earth orbital space, about 7000 in orbit to date
- Approximately 3,000,000 kgm at altitudes below 2000 km (most approximately 3 meters in diameter)
- High intersection angles produce high collision velocities
- If only a small fraction (0.01%) of the mass were in a smaller size range the resulting environment would exceed the meteoroid environment in that size range. Possible sources of smaller objects are:
  - Explosions
  - Hypervelocity collisions
  - Degradation of spacecraft surfaces
  - Solid rocket motors firing in space

NASA

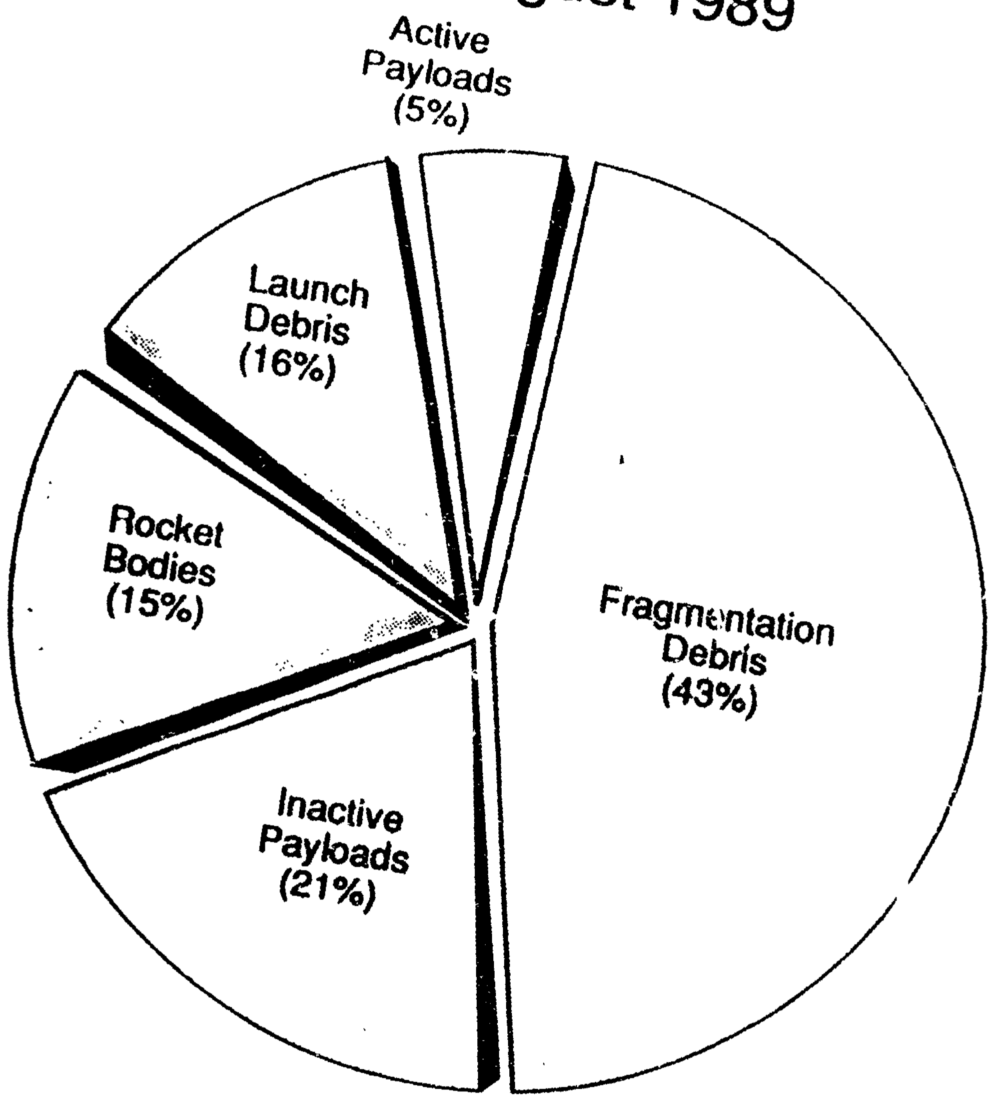
The orbital inclinations and altitudes of man-made objects are such as to cause the Earth to be surrounded almost uniformly by a shell. A spacecraft within that shell is almost equally likely to run into another orbiting object, independent of the direction of motion. Also the differences in the direction of motion between any two objects give relatively high encounter velocities, averaging about 10 km/sec.

Snapshot of Cataloged Objects as Observed from a Point in Space



Only 5% of the catalogued population is operational spacecraft; most are the result of the approximately [illegible]00 explosions in orbit.

Cataloged Earth Satellite Population
19 August 1989



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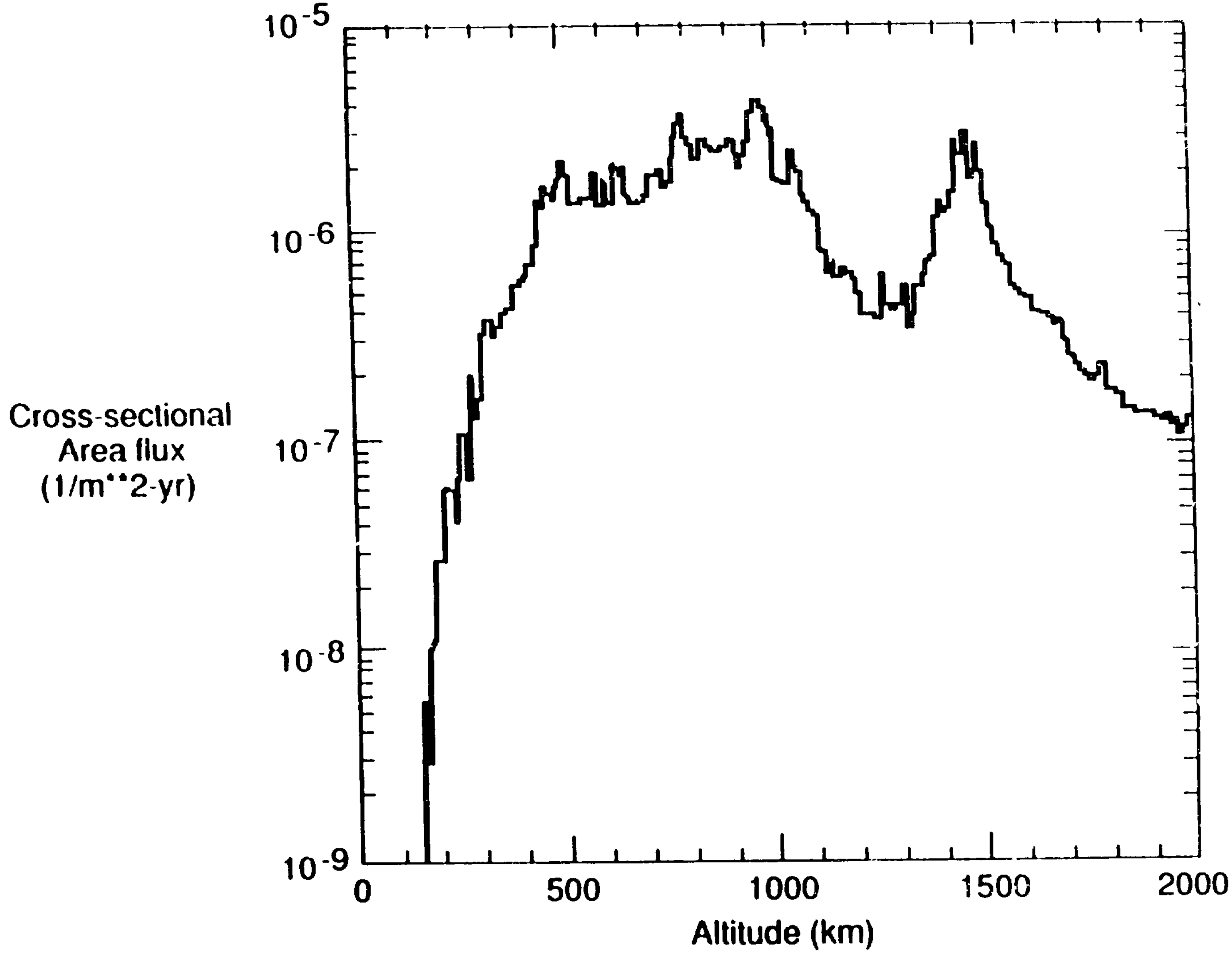
The flux from the 1987 catalogue is given here. The peaks in the fluxes at various altitudes are mostly the results of various breakups at those altitudes. If the Space Station were at about 450 km at this time, it would experience a flux of about 1E-6 per meter sq. per year. This means that there is about one chance in 100 every year of an object passing within 50 meters of the center of the space station, or about one chance in three over a period of 30 years if there were no change in the population.

US Space Command is also tracking a group of objects which are not catalogued, know as the analysis set. At altitudes below 500 km, the flux from the analysis set sometimes exceeds the flux from the catalogue; therefore, over 30 years, it is very likely that a collision with a catalogued or tracked object would occur, if there were no collision avoidance maneuvers. The current mission rule for the Shuttle is that it will consider maneuvering if a object is predicted to pass within a 2 km by 5 km by 2 km distance from the Shuttle. This is a cross-sectional area of about 40E6 sq. meters for the direction of most debris, and means that the Space Station would have to make 40 maneuvers per year if it used this mission rule. To reduce this rate means increasing the accuracy of the predicted miss distance so that unnecessary maneuvers are not performed.

USSPACECOM Cataloged Objects

January 1987



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During 1987, there were a large number of breakups, many at low altitudes. By looking at radar tapes at various sites, we know that as many as 1000 trackable fragments were produced from some of these breakup; however, only a small fraction were ever catalogued before they reentered.

1987 Satellite Breakups

Catalogued Fragments as of January 10, 1988

Breakup Date	Satellite Name	Breakup Altitude (km)	Orbital Perigee (km)	Orbital Apogee (km)	Orbital Inclin. (deg.)	Trackable Fragments Estimated	Trackable Fragments Cata-logued
1-28-87	COS1813	390	359	417	73	1000	190
7-26-87	COS1866	243	167	361	67	1000	9
9-18-87	ARIANE	?	246	36523	7	>15	1
9-21-87	COS1769	333	310	444	65	150	4
11-20-87	COS1646	406	401	434	65	150	25
12-17-87	COS1823	1485	1477	1523	74	>60	43
9-28-87 10-4-87	TIROS N	?	838	856	99	0	3

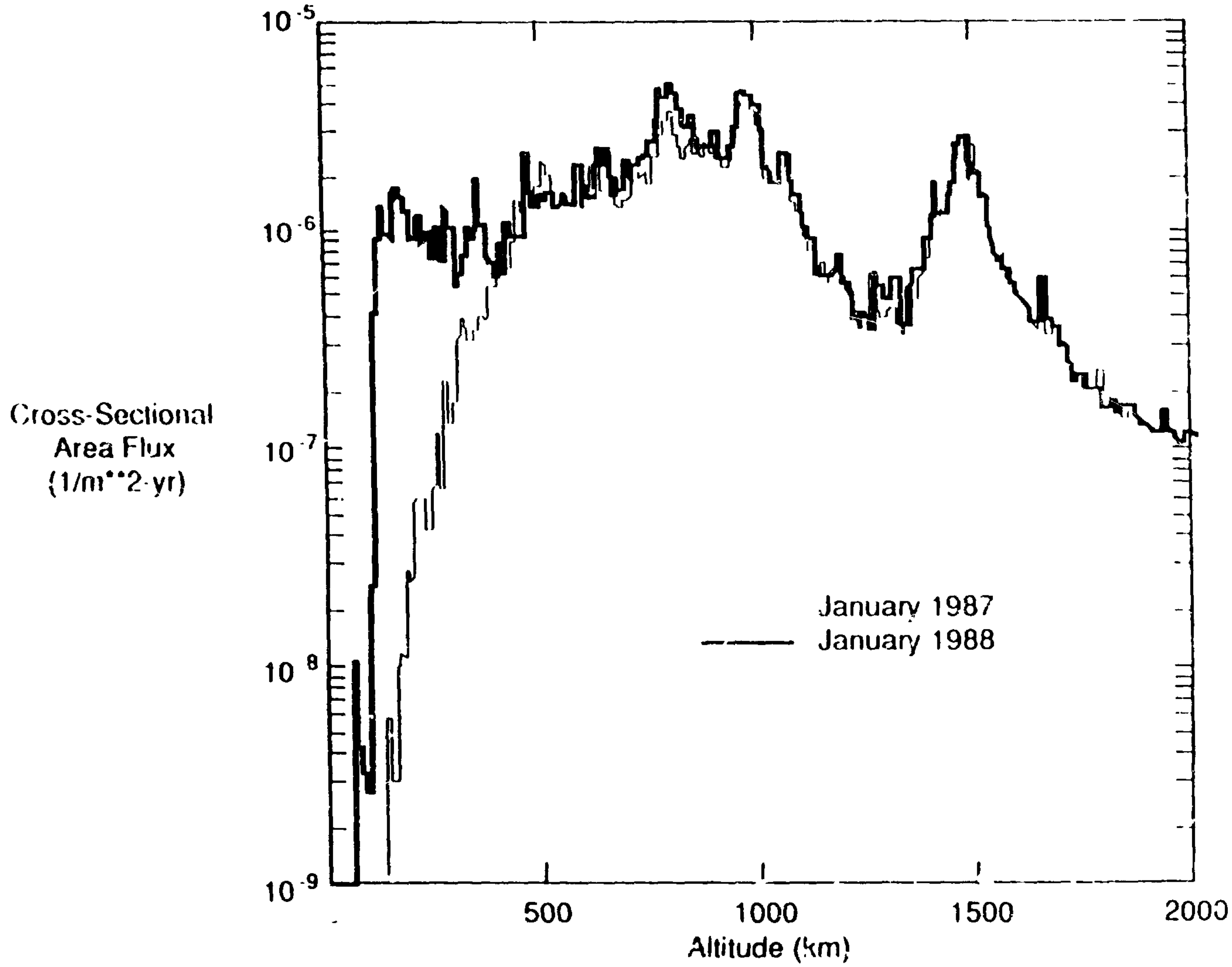
The estimated number of fragments was determined from radar data from individual radar sites.

NASA

The flux increases at low altitudes resulting from the cataloged fragments of the 1987 breakups alone were significant. If the Space Station were in orbit during this time the collision avoidance maneuver rate would have been significantly higher. However, the flux only remained this high for a few months before most of the fragments reentered.

USSPACECOM Cataloged Objects

January 1988



As solar activity increases, atmospheric density also increases, causing more debris to reenter, reducing the flux at lower altitudes. The 1990 solar activity may prove to be the highe[illegible] in record keeping.

Relationship Between Solar Cycle, Atmospheric Density, Debris Population

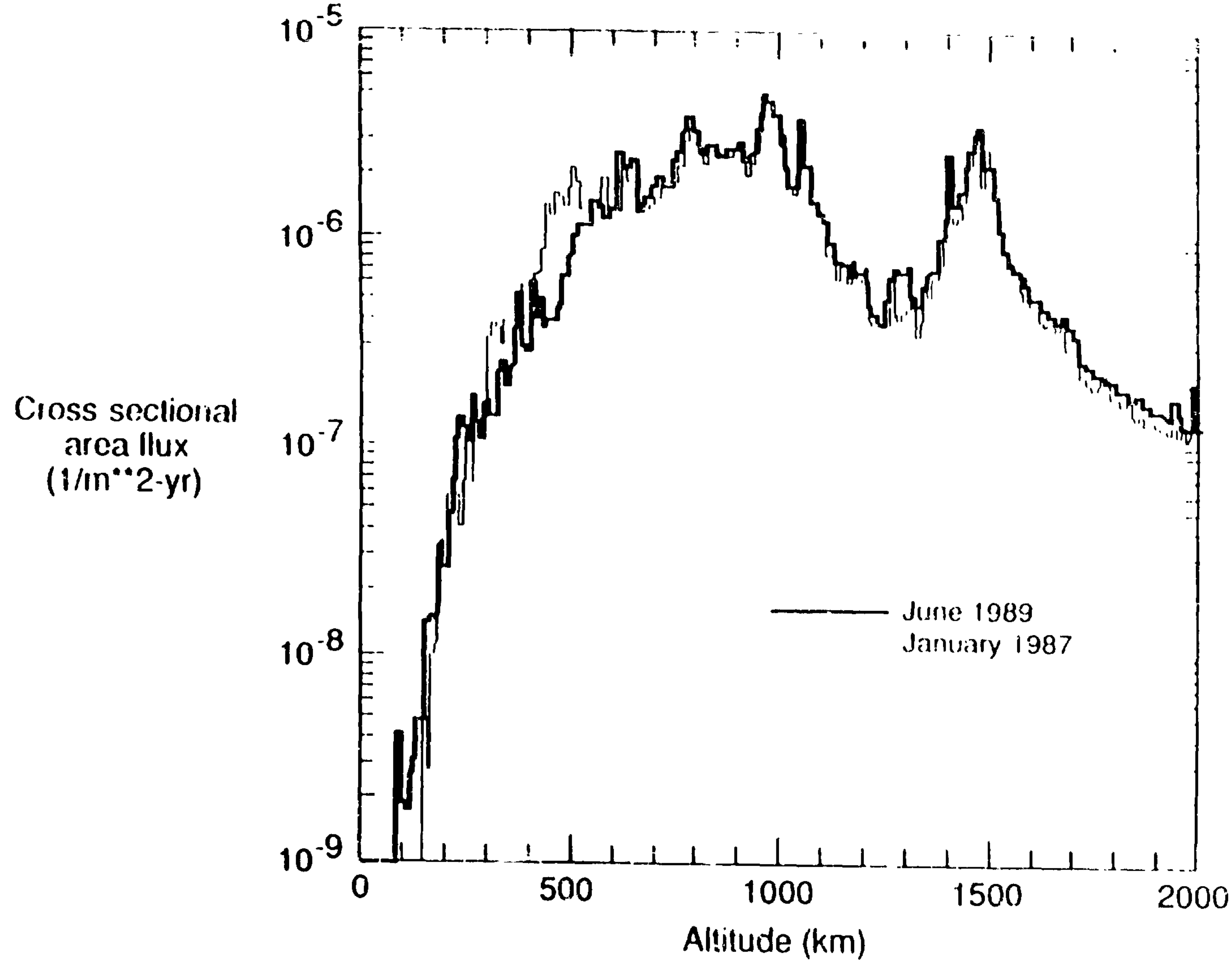
- 11 year cycle
  - Measured by sunspot number and 10.7cm radio wavelength ($F_{10.7}$) Flux
  - Average cycle $F_{10.7}$ ranges between 70 and 150
  - Last cycle (peaked in 1981) was above 200
  - Current cycle expected to be about 250
- High solar activity heats upper atmosphere
  - Atmosphere expands, moves up
  - Upper atmosphere density increases
  - Satellites, debris decay more rapidly
- Debris population changes with solar activity depending on altitude
  - Above 500 km atmospheric density so low, population not changed
  - Below 500 km, very noticeable changes

NASA

The effect that the currently high solar activity has been to reduce the flux at altitudes below 600 km; however, the high solar activity is also likely to require that the altitude of the Space Station be increased; consequently the flux that the Space Station is exposed will likely remain the same. As the solar activity again decreases, the flux at low altitudes will increase back to about its 1987 values with debris previously at higher altitudes now at these lower altitudes.

USSPACECOM Cataloged Objects

June 1989



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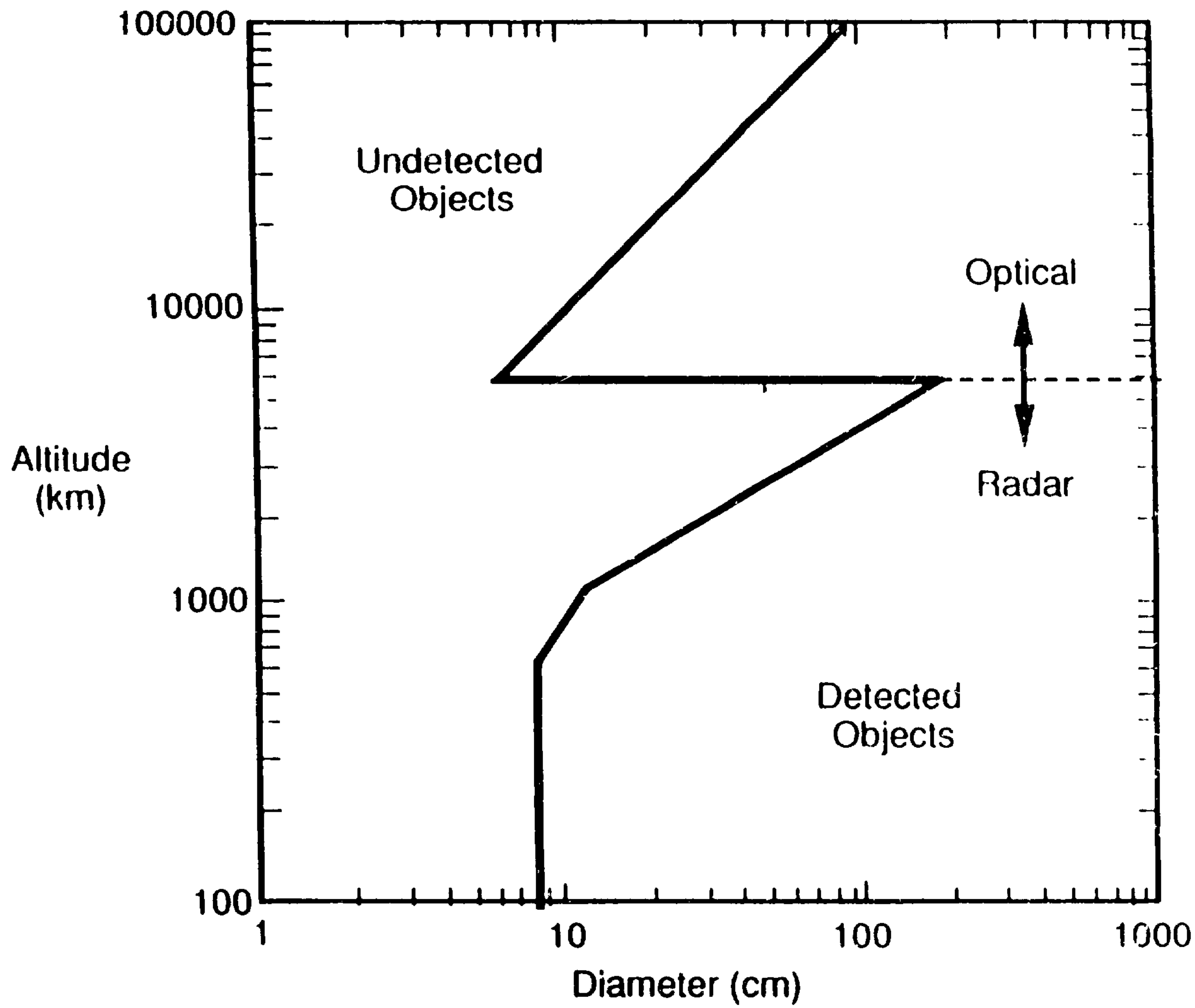
The US Space Command radars can only detect objects larger that about 10 cm, or larger, depending on the altitude. At low altitudes, this limitation is due mostly to the fact that the radars operate at a 70 cm wavelength, which is large compared to the diameter of the debris. A software limitation also limits the debris size to greater that 8 cm. The software limitation is required because the number of uncatalogued objects is too great to catalogue all detected objects with the existing system.

Sensor Altitude Limitations



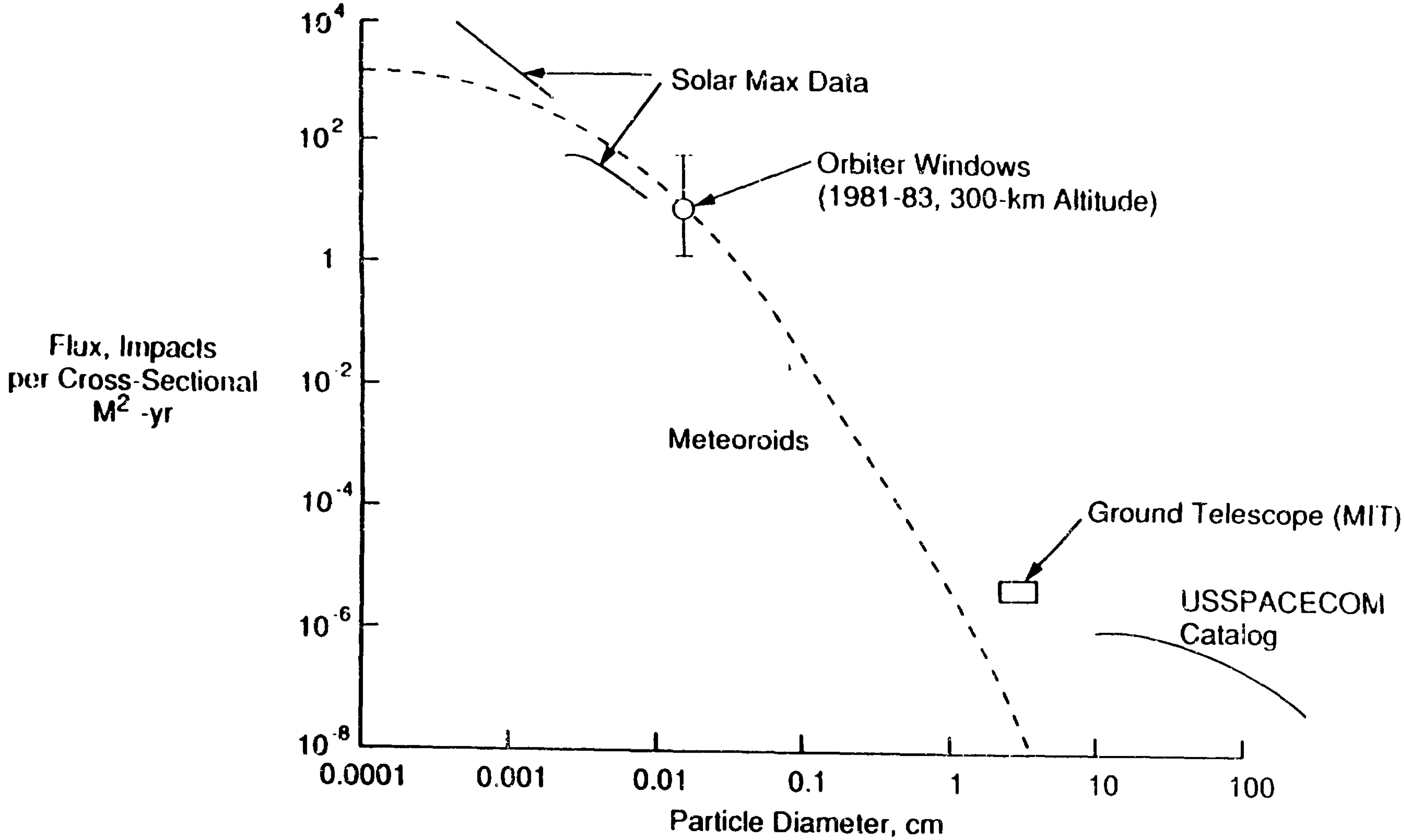
Experiments such as Skylab S149, the examination of the Skylab/Apollo windows, Explorer 46, Examination of the Shuttle window...all indicated an orbital debris population of small objects which were not catalogued.
However, the best data prior to 1989 were the US Space Command Tracked objects, the MIT Telescopic data, and examination of the return Solar Max Satellite surfaces.

MEASUREMENTS USED TO DEVELOP NEW ENVIRONMENT MODEL

- **US Space Command Tracked Data**
  - Catalogued plus analysis data sets
  - Assumed complete to 10 cm
- **MIT Telescopes**
  - Detected 3 to 5 times US Space Command Data predictions
  - Detection theshold 2 cm to 5 cm, as reported by MIT
- **Solar Max Satellite returned surfaces**
  - Both meteoroids and orbital debris detected
  - Detected 0.2 mm and smaller population

The best orbital debris data is compared with the meteoroid flux. The data indicates that the orbital debris flux is much larger than the meteoroid flux for sizes larger than about 1 cm, and smaller than 0.01 mm.

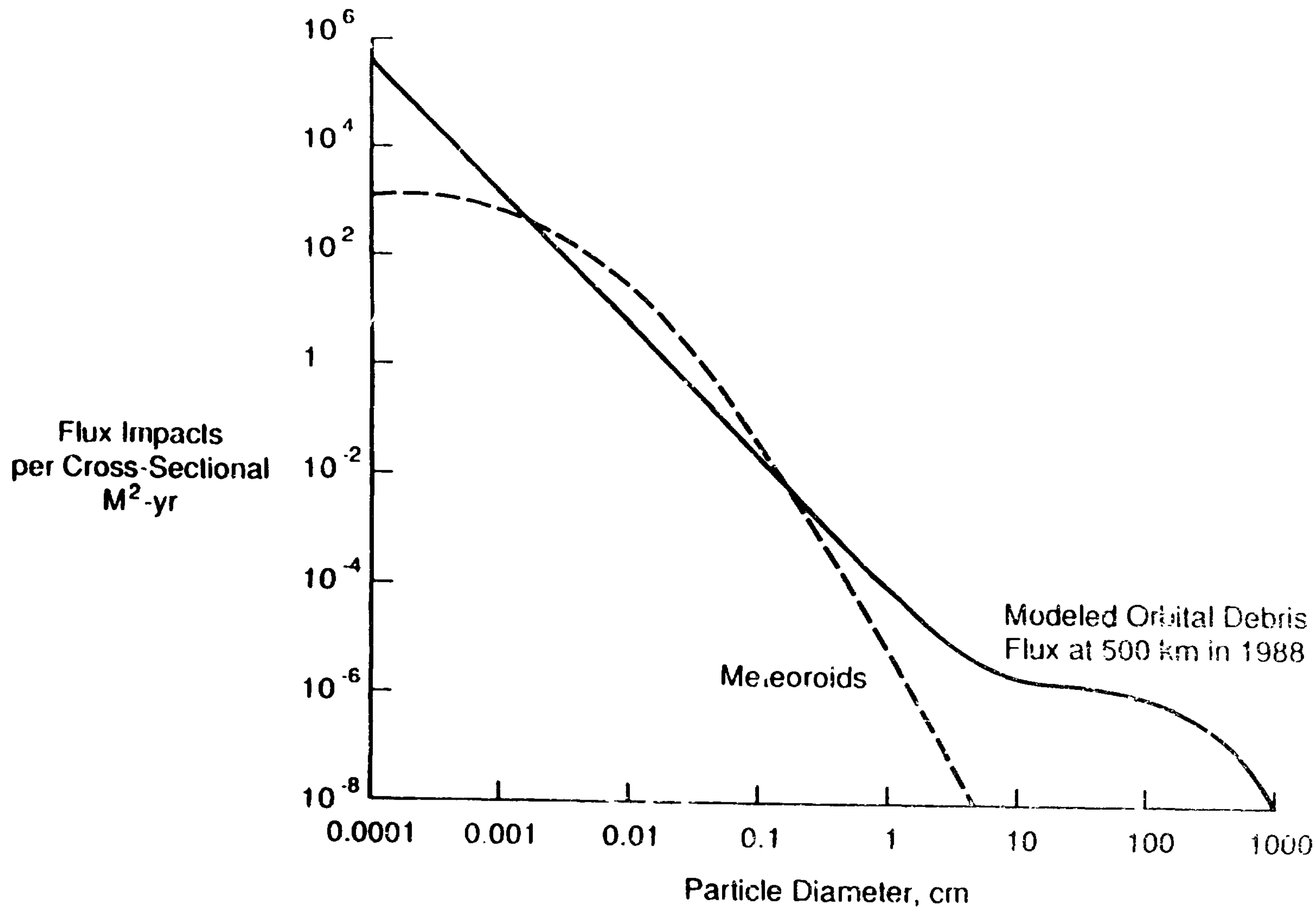
Summary of Data Sources



NASA

A curve was fit through the orbital debris data to obtain an orbital debris flux model at 500 km in 1988. The previous design flux of 1.8E-5 leads to an orbital debris design size of about 1.5 cm, vs. the 0.5 cm meteoroid design size. That is, to design to this debris environment on a 100 sq. meter of surface area to a .9955 probability of no penetration over 10 years will about triple the shielding weight over the meteoroid environment alone.

Modeled Data Sources



A 0.9955 probability of no penetration of a critical element may seem high; however there are many critical elements. With 20 critical elements, a 0.9955 probability of not losing a particular critical element becomes a 0.91 probability of not losing any one of 20 critical elements. If the amount of time is increased from 10 years to 30 years, the probability drops to 0.76. Therefore, reducing these probabilities may not be advisable.

The shielding is likely to be required to defend against something like a 1 cm debris particle. To defend against this size particle, the separation distance between the bumper and the back sheet should be at least 25 particle diameters. This is causing some engineering problems. At a total shield weight of 2.8 gm/cc, expected for a conventional Whipple bumper, the total shielding weight would be 56,000 kgm for 20 elements. While the weight of the shield could be reduced by using more advanced shielding concepts, the size of the debris particle which must be defended against could be larger. In any case, it is likely that the total shielding weight will require extra shuttle flights to place the Space Station into orbit.

Example Shielding/Reliablity

for Space Station

Assume 0.9955 probabiltiy of no failure of each critical element for 10 years

- 0.91 Probability of no failure of any one of 20 critical elements in 10 years

- 0.76 Probability of no failure of any one of 20 critical elements in 30 years

Assume each critical element is 100 m surface area, and protected against 1 cm projectile at 10km/sec., using conventional aluminum bumper.

- Optimal shield requires at least 25cm separation

- Shield weight approximately 56,000kgm for 20 elements

Understanding the environment has some critical weight issues associated with the Space Station. In 1989, three tests were performed to test the model environment. These tests used the Arecibo Radar in Puerto Rico, the Goldstone Radar in California, and US Space Command's GEODSS telescopes located both a Diego Garcia and Maui, Hawaii. The largest surprise came from the telescopic data which indicated that there are two to three times as many objects in orbit to a limiting size of 10 cm than indicated by the catalogue.

1989 TESTS TO NEW ENVIRONMENT MODEL

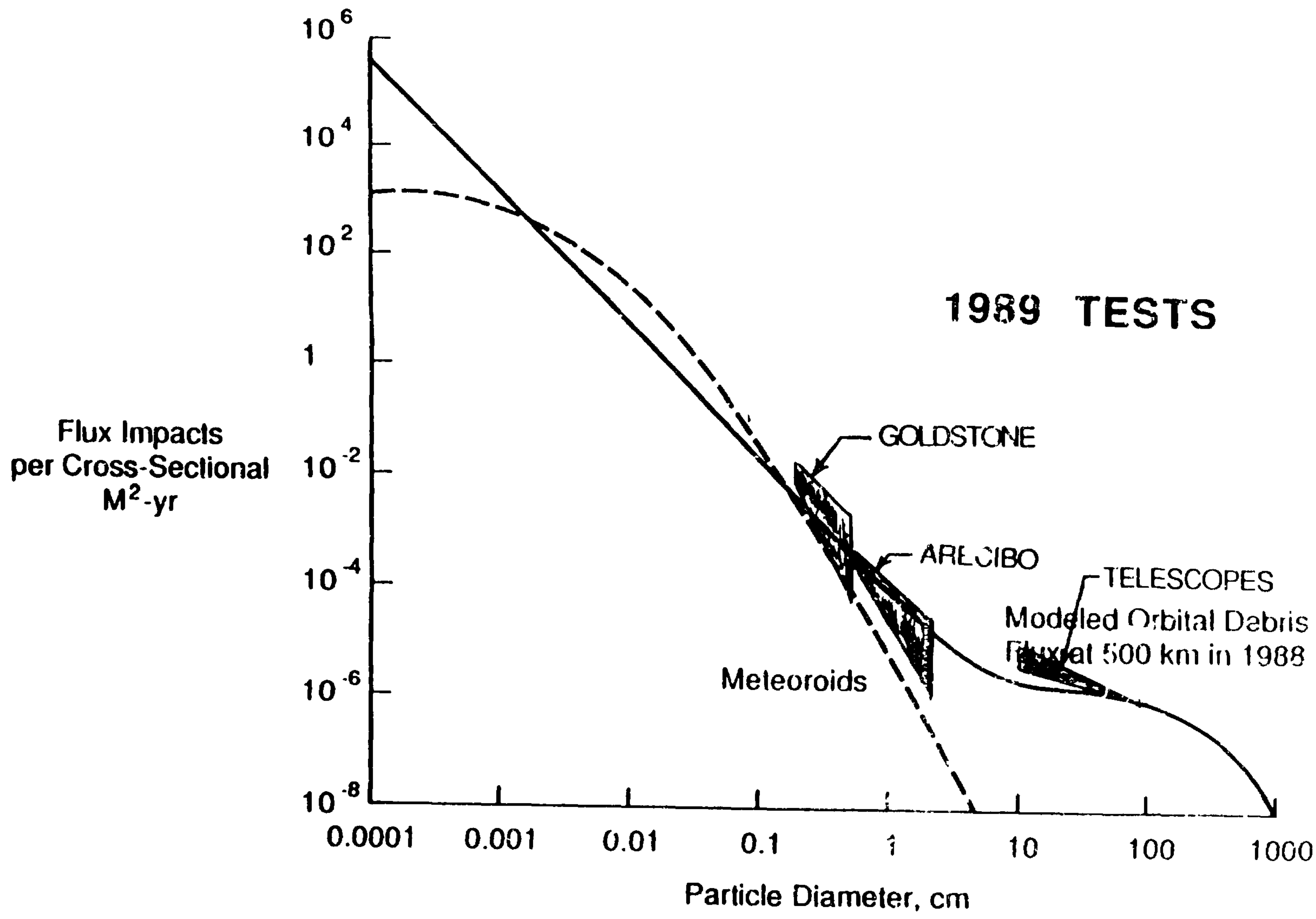
- Arecibo Radar
  - 18 hours observation
  - 12.6cm radar wavelength
  - 0.5cm to 2cm debris detected
  - Agreed with model within uncertainty of data

- Goldstone Radar
  - 14.5 hours observation
  - 3.5cm radar wavelength
  - 0.2cm to 0.5cm debris setected
  - Agreed with model within uncertainty of data

- US Space Command Telescopes (GEODSS)
  - More than 20 hours analyzed
  - Larger than 10cm debris detected
  - Model too low for sizes between 10cm and 1 meter
  - Model maybe too low for sizes between 2cm and 10cm.

Within the errors of measurements, the two radar experiments agreed with the model environment; however, the telescopic data indicates that the model is too low for sizes larger than 10 cm, any possibly too low for sizes between 2 cm and 10 cm. However, we still do not have any good measurements of debris between 1 cm and 10 cm.

Modeled Data Sources



NASA

To collect data on debris sizes between 1 and 10 cm, we have an agreement with US Space Command, where they will collect data using their Haystack radar and build and operate an Auxiliary radar. In exchange, NASA will pay for the construction of the Auxiliary radar. These two radars will have sufficient data by 1992 to update the environment model, if necessary, in time for CDR's.

Long term debris monitoring is planned by GBR-X, a large, X-Band radar planned to be constructed nearer the equator on Kwajalein.

12/5/89

ORBITAL DEBRIS RADAR PROGRAM

CURRENT STATUS

- U.S. DEPARTMENT OF DEFENSE SUGGESTED ALTERNATIVE TO DEDICATED ORBITAL DEBRIS RADAR

- NEAR-TERM DATA COLLECTION

  - HAYSTACK
    X-BAND; 10 GHz
    0.05° BEAMWIDTH
    400 KW PEAK POWER
    1 - 5 MSEC. PULSE; UP TO 50% DUTY CYCLE
    1 CM. DIAMETER AT 500 KM ALTITUDE
    10° ELEVATION ANGLE TO REACH 28° ORBITS WITH 1700 KM SLANT RANGE

  - HAYSTACK AUXILIARY
    Ku-BAND; 16.7 GHz
    0.15° - 0.3° BEAMWIDTH
    100 KW PEAK POWER
    0.25 - 5 MSEC. PULSE; UP TO 30% DUTY CYCLE
    1 CM. DIAMETER AT 500 KM RANGE
    VERTICAL STARING; ONLY ABLE TO REACH 42° ORBITS

Projecting the future environment is very difficult. Already changes in operational practices are likely to reduce the number of satellite breakups in the immediate future; if so, the current projections should be reduced. However within the next 10 to 20 years, random collisions between non-operational satellites are likely to cause the breakup rate to again increase. If so, the long term environment could increase faster than the model projections.

Projecting Future Environment

- Must assume debris sources, solar activity
  - Traffic models (increase launch rate?)
  - Satellite fragmentation rates
    - Future accidental explosions? Type?
    - Military test?
    - Random collision fragmentation tied to traffic model
  - Unmodeled sources?
  - Solar activity not always as predicted
- Current model assumption
  - Accumulation of large debris continues 5% increase per year (near term)
    - World launch rate does not significantly increase
    - Accidental, intentional fragmentation remains constant (5 per year)
    - Random collision fragmentation increases
  - Accumulation of small debris increases at 10% per year
    - Expected from random collisions within few years
    - May cover unmodeled sources within immediate future
  - "Average" solar cycles after next cycle

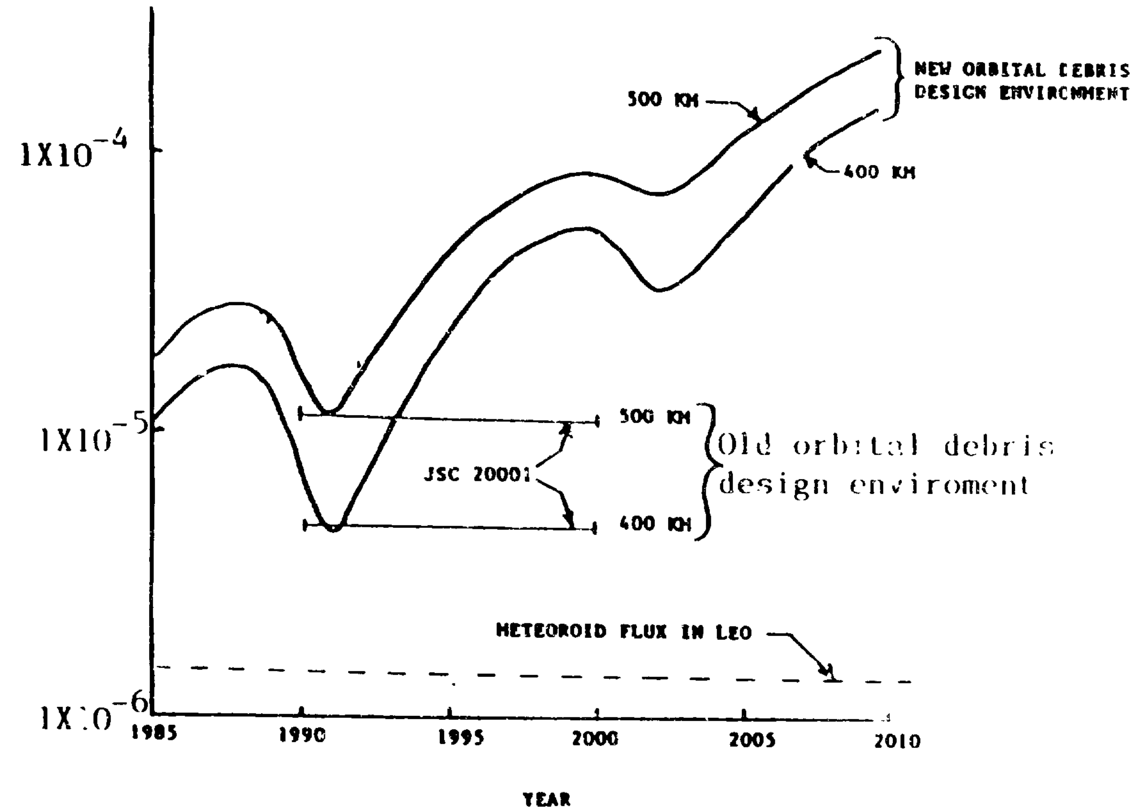
NASA

The new environment is time dependant, and changes with solar activity. The new and old models are only in agreement near the maximum of the current solar cycle. The high values and large uncertainty in this projection increases the problem of shielding the Space Station.

New Orbital Debris Design Environment

Example Output for 1 cm and Larger Orbital Debris

Flux, impacts per sq. meter of cross-section per year for 1 cm and larger



- **Compared to JSC 20001**
- **Compared to Meteoroid Environment**
- **Inputs Assume**
  - **Nominal Traffic Model**
  - **Expected Solar Activity**

There is uncertainty in both the current and projected environment. In addition, there is an uncertainty in the consequences of the environment (e.g., how critical is a penetration into a critical element?). The Space Station design must be able to accommodate to these uncertainties and respond to new data as the uncertainties are reduced. One way of doing this is to build the Space Station so that all critical elements are protected to some level, and are designed such that new protection can be added, if necessary. Shielding alone may not be practical; collision warning, doors that close automatically, selective heavily shielded areas, and other techniques may be required to obtained the desired level of safety. The Space Station design should not exclude these possibilities.

SUMMARY

- Current Environment is uncertain
  - Best Estimate contained in TM 100-471 (new environment)
  - Improved Environment Model expected before CDR's
  - MIT Haystack, Haystack Auxiliary radars
  - LDEF
  - Experiments with Eglin, Goldstone radars and Ground telescopes

- Future Environment is uncertain
  - Planned Traffic Models show long-term increases in population
  - Changes in operational practices could result in short-term decreases
  - US, ESA, Japan already making changes
  - Discussions with USSR
  - Environment will be monitored by GBRX, Space Station Cosmic Dust Facility, Future experiments

- Space Station design requirements should
  - Meet short-term safety and maintaince needs
  - Respond to increased knowledge of the environment and vulnerablilty to the environment